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By Atwood R. Heath, Jr.

NASA Langley Research Center
Langley Station, Hampton, Va.

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INTRODUCTION

A survey has been made of organizations known to be active in the solar energy collector field in order to determine the status of the technology at this time. The selected method of conversion of solar energy to electricity with the attendant different temperature require-ments, governs to a large extent the line of approach to lightweight concentrator concept and construction taken by any organization. These different lines of approach result in a varied assortment of collectors that range from very lightweight mirrors such as inflatable plastic models, to relatively heavy one-piece mirrors. With such diverse activ-ity in the field, a summary of the properties of the various types is needed to indicate the overall picture of the accomplishments to date.

Specifically, a summary is made of the efficiency, concentrating ability, unit weight, and packaged volume of solar energy collectors fabricated to date.

Description of Fabricated Collectors

Figure 1 presents sketches of six different concepts of lightweight solar energy collectors. These six concepts are not the only ones being considered, but they are the concepts that have been developed to a point where quantitative data on their capabilities exist. Examples of

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*Aero-Space Engineer.

the six types are listed in table I with some of their pertinent charac-
teristics. For two types, additional collectors fabricated by different
methods and materials of construction are also presented. A brief
description of each of the types with some details of the materials and
methods of fabrication follows.

The Fresnel collector[1] is shown in figure 1 and the folding
arrangement which consists of four hinged panels is indicated. The
Fresnel surface is made by electroforming nickel on a steel master that
has been machined and polished. The Fresnel electroform is then bonded
to an electroformed stiffening structure.

Shown next on figure 1 is one form of an inflatable type collec-
tor[1]. The collector is pressurized and is formed of an aluminized
Mylar paraboloid and a clear Mylar front cover. An inflated torus also
made of Mylar is attached to the outside of the collector at the junc-
tion of the reflecting surface and the front cover. The reflective sur-
face is stretch-formed during fabrication.

A sketch of the inflatable-rigidized collector[2,5] is shown next.
Basically, this collector is an aluminized plastic paraboloid which is
rigidized in space by the application of a foamed plastic to the back
of the collector. The collector that is discussed in this paper is a
feasibility model for use in ground tests.

The next sketch shows a one-piece collector[6,7]. One method of
fabricating this type collector consists of electroforming a thin dish
of nickel on an appropriate master. The dish is then stiffened by the

addition of an electroformed torus to the periphery of the dish. Another
method of one-piece collector construction utilizes a honeycomb sandwich
that consists of a cast epoxy plastic-reflecting surface bonded to an
aluminum honeycomb which is in turn backed up by a plastic Fiberglas panel.
The reflective face can be cast on any suitable convex master. Several
collectors have been made by this method of construction[8]. Several
other one-piece collectors have been constructed by methods such as spin
casting of plastic[9] and hydroforming of aluminum[10], but complete
quantitative data on the capabilities of these collectors are not
available.

Next is shown a sketch of a petal collector. There are several vari-
ations of this type, but in all cases, the collector consists of a hub
with attached petals which fold up to form a compact package for launching.
A deploying system consisting of springs, cables, or mechanical linkages
is used to open these devices. Several collectors of this type have been
built, and different methods have been used in the construction of the
petals for each. One collector[1] had petals of electroformed nickel,
monocoque construction. Two others had petals of honeycomb sandwich which
consisted of an aluminum reflecting face, honeycomb and back, one was a
32.2-foot-diameter model[9] and the other was a 15.75-foot-diameter
model[11]. Another[12] had petals formed of a thin aluminum face which
was stiffened by a light aluminum lattice truss spot welded to the back.

The last sketch shows a typical umbrella collector[13]. This col-
lector consists of an aluminized Mylar covering stretched over metal ribs.
This collector also had an operational pneumatic erecting mechanism.

COLLECTOR EFFICIENCY

The important feature of a collector is the ability to collect the solar radiation efficiently and to provide the proper degree of concentration of the radiation commensurate with the ability of the conversion system to utilize the heat. The data presented herein were obtained by means of cold calorimeters which are essentially heat absorbers which operate at slightly above ambient temperatures. At these temperatures, reradiation from the calorimeter is very small, and the measured efficiency is only a function of the collector geometry and reflectivity.

Figure 2 shows the efficiency as a function of concentration ratio for a representative group of collectors. The collector having the highest efficiency and concentration ratio has been chosen where several collectors of a specific type exist. A cavity calorimeter was used in all instances but one. The umbrella was tested with a spherical calorimeter because the collector rim angle was 90° thus making the cavity type unsuitable. The efficiency is based on the projected net reflective area. The concentration ratio is based on the ratio of the projected net reflective area to the calorimeter aperture area. For the umbrella collector, the calorimeter aperture area is replaced by the surface area of the spherical receiver. All of the collectors had a reflective surface of vapor-deposited aluminum.

As might be expected, the one-piece electroformed nickel collector[6] is superior to the expandable collectors in geometry as indicated by the higher efficiencies at the higher concentration ratios. Also included in

this figure is the theoretical curve for this collector calculated for a reflectivity of 0.91. It can be seen that the data for this collector approach the theoretical curve very closely which indicates that the master is of good quality and the reproduction process is very faithful.

The next most efficient collector at higher concentration ratios is the 15.75-foot-diameter aluminum honeycomb petal model. A calculated efficiency curve based on the measured geometry of the petals was made[11] and was found to be about 0.10 higher than the measured values of efficiency. This discrepancy is thought to be due to inaccuracies in the measurement of the petal geometry plus convective heat losses from the calorimeter cavity due to wind.

The inflatable-rigidized and Fresnel collectors fall very close together on this figure. Planet photos made with the Fresnel collector[1] indicated that the outer edges of the serrations deviated from a conical shape due to difficulties in polishing the steel master. Also deviations in geometry due to the effects of the backing structure bond to the reflective face were noted. One further cause of low efficiencies for this collector is the inherent shadowing problem of the Fresnel mirror. The inherent shadow area is 15 percent of the total area; thus, if this 15 percent were removed from the total reflective area, the efficiency calculated on the basis of the reduced area would be 0.61 instead of 0.51 at a concentration ratio of 1,000. The inflatable-rigidized collector has been tested with a calorimeter that effectively had only two different apertures so the exact variation of efficiency with concentration ratio

is difficult to determine. An "orange peel" effect was observed in the reflective surface of this collector, but no assessment of adverse effects, if any, could be made. Lower efficiencies could also result from the use of commercial aluminized Mylar which has a reflectivity of only about 0.83.

The inflatable paraboloidal concentrator gave relatively low estimated efficiencies in the concentration ratio range near 1,000. The low efficiencies were attributed to the large transmission and reflectance losses from the transparent front face as well as reflectance and transmission losses of the reflecting surface. The relatively flat curve of efficiency with concentration ratio indicates that the geometry of the reflecting paraboloid is good up to concentration ratios of about 2,500 where a sharp decrease in efficiency occurs.

The concentrating ability of the umbrella collector is much below the ability of any of the other collectors shown in figure 2. The main problem with this type of collector concerns the shape of the reflecting surface gores between ribs. The gores have a tendency to take a shape which is nonparaboloidal; thus, a lower concentration of the sun's rays results. The number of ribs used to form the collector determines to some extent the concentrating ability, with a greater number of ribs giving better concentration. A spherical absorber was used for this collector; therefore, it is difficult to compare this collector to the others of figure 2 because cavity absorbers were used.

Figure 3 shows the efficiency-concentration ratio curves of two one-piece collectors, the electroformed nickel[6] shown previously on

figure 2 and a cast plastic-aluminum honeycomb model[8]. The geometry of the plastic collector is not as good as that of the electroformed collector as indicated by the steeper slope of the efficiency curve. This is not surprising in view of the fact that two more replication steps were required to arrive at the plastic collector, than was used to get the nickel collector. The latter was electroformed on a glass search-light master while the former was cast on a plastic master which had, in turn, been cast from a metal searchlight mirror of uncertain quality.

Figure 4 shows the efficiency curves of three petal collectors, one, the 15.75-foot-diameter model[11] was shown on figure 2, and the others are the electroformed nickel collector[1] and the 32.2-foot-diameter stretch-formed, aluminum-honeycomb collector[9]. All three collectors are in the same general range of efficiency and concentration ratio. The electroformed collector had petals with a degraded reflective surface due to unsatisfactory protective coatings. The efficiencies shown on figure 4 would be about 0.12 higher if better coatings had been used. This would give an efficiency of 0.80 at a concentration ratio of 600. The data for the 32.2-foot-diameter collector are for one petal only and do not reflect the problems associated with petal alinement. The petal showed honeycomb markoff and roll marks. The roll marks were removed by a mechanical polish but diffusion of light from the polish scratches was still evident. An epoxy layer over the polished aluminum has been effective in increasing the reflectivity and the markoff has since been reduced by better control of the bonding agent used. No calorimetric

tests have been made since the improvements to the petals were completed. The stretched-formed lattice-truss collector[12] was tested only by optical ray-tracing methods but a general idea of the quality of this collector can be obtained by comparison with two other collectors that were tested by the same method as well as by calorimetry. If a reflectivity of 0.86 were assumed, the collector efficiency would fall slightly below the data for the electroformed collector.

Collector-Absorber Operating Temperatures

The curves of figure 2 indicate only the efficiencies of the collectors, that is, no reradiation occurs from the calorimeter. A collector must be combined with an absorber that radiates at its operating temperature to find the temperature capability of the collector. For purposes of analysis, a cavity absorber is assumed with an absorptivity and emissivity of 1.00. The solar constant which affects the reradiation term is assumed to be 130 watts per square foot. The efficiency data of figure 2 are used in combination with reradiation losses of the assumed absorber to obtain the efficiencies of the combinations as a function of temperature as is shown in figure 5. At a given temperature, the efficiency shown is the maximum obtainable and represents a specific concentration ratio. It is seen that, if a thermionic conversion system with temperatures near 4,000° R is required, only the electroformed one-piece mirrors are capable of efficient operation at the present time. All of the expandable collectors are relatively inefficient even at temperatures around 2,000° R.

Collector Weights

The unit weights of the collectors discussed so far as well as some that were built but have not been completely evaluated are shown in figure 6.

The inflatable-rigidized collector has a very high unit weight of 3.82 lb/ft^2. This collector was a ground test model and was not intended to represent flight hardware weight. An estimated weight curve made by the manufacturer for a flight article which could be made at the present time is shown. The unit weight approaches 0.2 lb/ft^2 for collectors with diameters above 30 feet.

The unit weights of the one-piece collectors vary from 0.40 lb/ft^2 to slightly over 1.00 lb/ft^2. The collectors with unit weights of 0.40 and 0.70 lb/ft^2 had definite problems with geometry so it can be expected that one-piece collectors with good geometry will weigh roughly 0.9 to 1.0 lb/ft^2 for construction by methods discussed so far.

The Fresnel mirror has a unit weight of 0.46 lb/ft^2 which is about half that of the one-piece collectors. Most of the petal model weights are about half that of the Fresnel. Roughly it can be expected that the furlable type can be made to weigh about 0.20 lb/ft^2 for petals alone for diameters at least to 32 feet. The addition of hubs and erecting mechanisms will add to this unit weight; for example, these components weighed 0.07 lb/ft^2 for the 32.2-foot-diameter collector[9].

The umbrella collectors have unit weights of about 0.11 lb/ft^2 which includes the ribs, hubs, and plastic covering. Calculations in

reference 13 indicate that this weight will increase with collector diameter as shown in the figure. The 10-foot-diameter collector was equipped with a pneumatically operated unfurling mechanism which was powerful enough to operate a 50-foot-diameter collector. Based on the larger diameter, the unit weight of the mechanism would only be 0.01 lb/ft^2. Therefore the weight of the unfurling mechanism could be negligible for large-diameter collectors.

The lowest unit weight of any collector shown is 0.03 lb/ft^2 for the inflatable model. This weight is based on the use of 1-mil plastic and does not include any inflation gear. The low unit weight of this collector makes it of interest, in spite of the many obvious problems such as environmental limitations associated with the concept.

Figure 7 shows the specific powers of the collectors shown in figure 5. The combined collector-absorber efficiencies of figure 5 were used with the unit weights of the various collectors and a solar constant of 130 watts/ft^2 to obtain the values shown. The inflatable collector delivers the most heat per pound for absorber temperatures below about 3,500° F due to the extremely low unit weight of the collector. On the other hand, the very efficient one-piece electroformed collector has a relatively low value of specific power due to its heavier weight. However, when comparing these two collectors at the same value of specific power, the inflatable would be many times the size of the one-piece collector for power systems of the same output. The inflatable-rigidized collector has a very low specific power because the weight of the ground

test model was used. The petal collector shown in this figure has a relatively low value of specific power because basically it was to be used as a ground test model also, and thus was fairly heavy. The efficiencies for this collector were previously shown on figure 4 with two other collectors, the electroformed nickel petals[1] and the 32.2-foot-diameter aluminum-honeycomb petals[9]. Both of these latter collectors have values of specific power about five times greater than the power for the collector shown, due to much lower specific weights.

Packaged Volumes

The packaged volumes of the various types of collectors are shown in figure 8. It has been assumed that each paraboloidal collector will fit into a cylindrical shape and that the folded Fresnel collector will fit into a rectangular prism.

The one-piece collectors have the highest volumes for a given diameter because it has been assumed that no folding would be practical. Of course the limiting factor for one-piece models is the launch vehicle diameter and the packaged volume as determined could be relatively meaningless.

The petal collectors are the next highest in volume, which runs to over 700 cubic feet for a 32.2-foot-diameter collector. Minor reductions in the volume of this type of collector might be made; however, no radical reduction in volume is expected.

The umbrella collector has a fairly low volume at least for the 10-foot model. The collector can be packaged in a long slender cylinder

which might present some problems. Collectors have been proposed in which the ribs would have more than one folding joint. This scheme would, no doubt, give a package that is more easily managed.

The Fresnel collector has a very low volume in the 4-foot model, but the inflatable-rigidized collector has the most favorable packaged volume of any collector shown, especially in the larger sizes. The curves show estimated values of volume that can presently be achieved.

No volume is given for the inflatable collector, but it seems possible that this collector can be packaged as efficiently as the inflatable-rigidized collector.

CONCLUDING REMARKS

In summary, a survey of the state of the art of solar energy collector technology has been made and a brief discussion of the various areas of accomplishment follows.

One-piece electroformed nickel collectors that closely approach the theoretical concentrating ability and efficiency have been fabricated. The unit weights of these collectors fall in the range of 0.90 to 1.00 lb/ft^2. The delivered energy per pound of collector weight is relatively low for these collectors but they are capable of attaining higher absorber temperatures (greater than 4,000° R) than lighter collectors.

Other types of collectors such as petal, Fresnel, inflatable, and inflatable-rigidized fall in the concentration range of about 500 to

5,000, which would make them suitable for lower temperature requirements (around 2,000° R). The inflatable type has a very high ratio of delivered energy to collector weight (1,200 watts/lb at 2,000° R based on plastic weight only) while the petal models yield around 575 watts/lb which is about three times that of the one-piece collectors. The unit weights for the various types range from 0.03 lb/ft^2 for the inflatable to 0.46 lb/ft^2 for the Fresnel.

The umbrella collector has a very low concentrating ability which is in the range of 25 to 400. The temperature range for this collector thus falls around 1,000° R. At this temperature the collector yields about 750 watts/lb due to the low unit weight.

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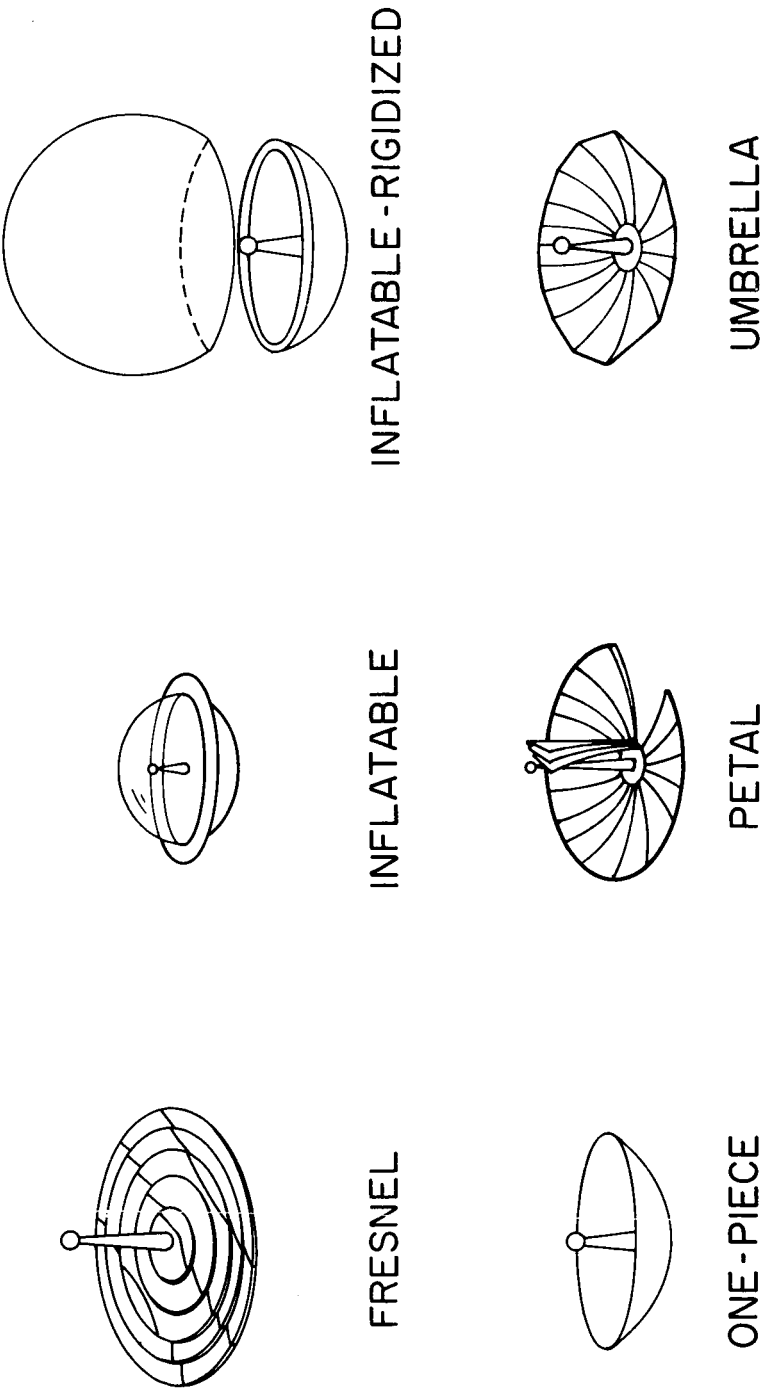
TABLE I

EXAMPLES OF FABRICATED SOLAR COLLECTORS

Type	Method of construction	Material	Rim angle, deg	Diameter, ft	Net projected reflective area, ft²	Reflective material	Measured reflectivity	Unit weight, lb/ft²	Reference
Fresnel	Electroformed	Nickel	40.00	4.00	12.10	Aluminum	0.85	0.46	1
Inflatable	Stretch formed	Mylar	53.13	4.27	13.00	Aluminum	-----------	[b]0.03 est	1
Inflatable-rigidized	-----------	Mylar-foam	60.00	10.00	76.00	Aluminum	-----------	3.82	2 to 5
One piece	Electroformed	Nickel	61.50	5.50	19.77	Aluminum	0.89 - 0.90	0.96	6
One piece	Cast plastic	Epoxy-fiberglass	60.50	5.00	18.69	Aluminum	0.755 ± 0.1	0.94	8
Petal	Electroformed	Nickel	53.13	4.27	13.00	Aluminum	-----------	[a]0.20 - 0.40	1
Petal	Stretch formed	Aluminum honeycomb	45.00	15.75	173.80	Aluminum	0.86	1.00	11
Petal	Welded lattice Truss	Aluminum	45.00	10.00	75.97	Aluminum	-----------	[a]0.29	12
Petal	Stretch formed	Aluminum honeycomb	52.00	32.20	745.00	Aluminum	0.85	[a]0.18	9
Umbrella	60 Al. ribs	Mylar	90.00	10.00	77.81	Aluminum	0.83	[c]0.11	13

[a]Petals only.
[b]Mylar only.
[c]Ribs and Mylar only.

INFLATABLE-RIGIDIZED

UMBRELLA

NASA

INFLATABLE

PETAL

FRESNEL

ONE-PIECE

Figure 1.- Types of solar collectors.

18
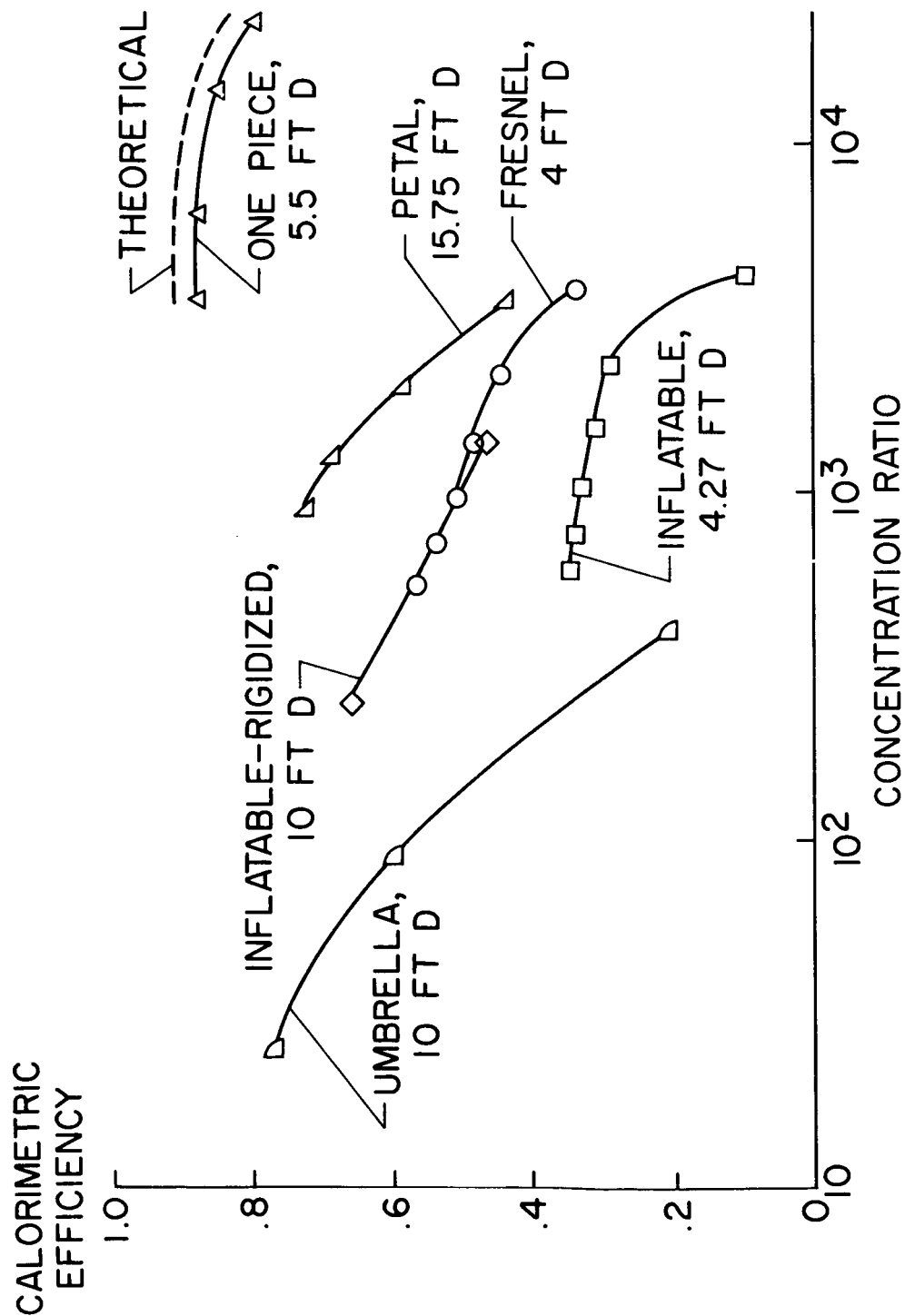
Figure 2.- Collector efficiency.

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CALORIMETRIC EFFICIENCY

NICKEL, 5.5 FT D

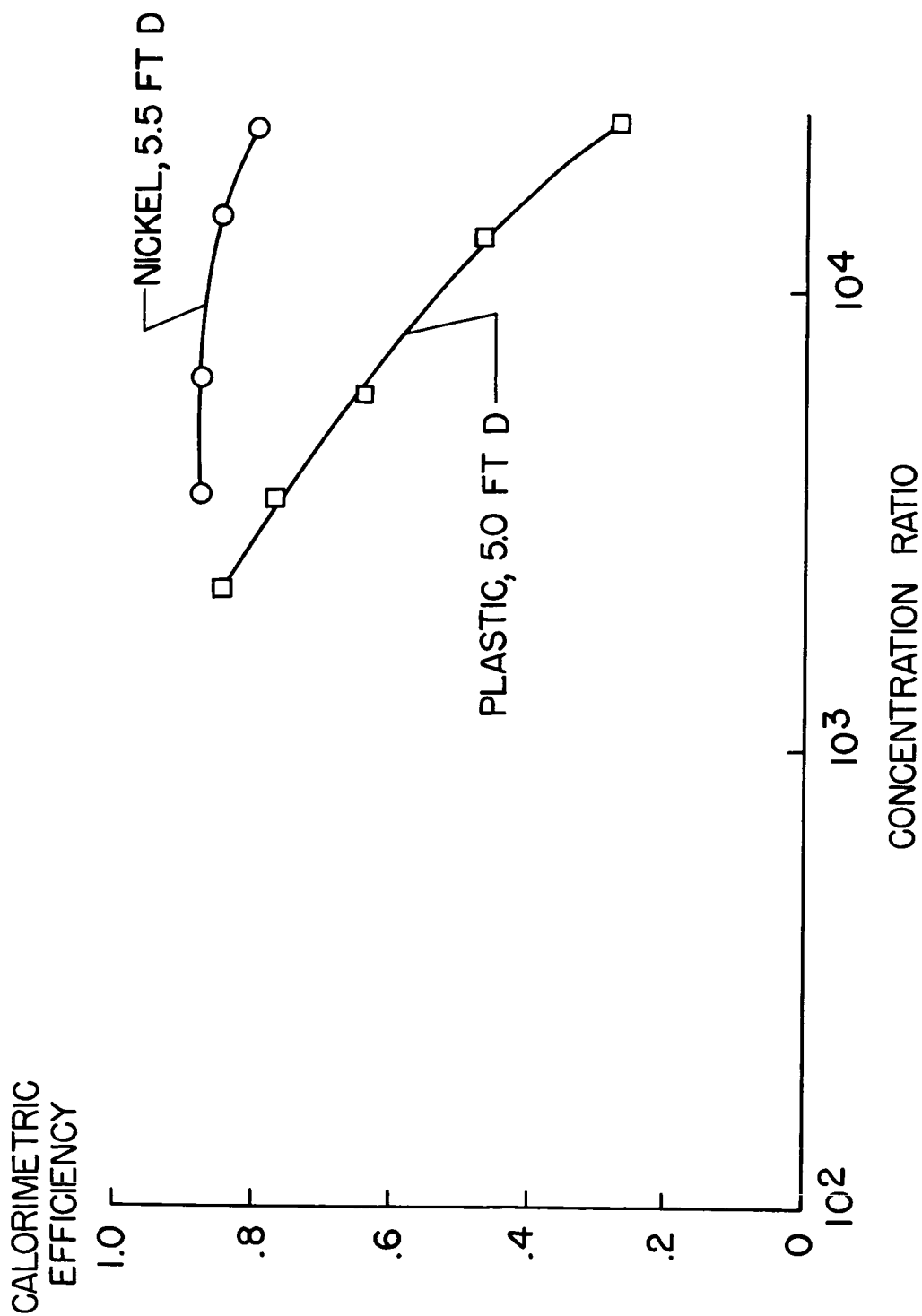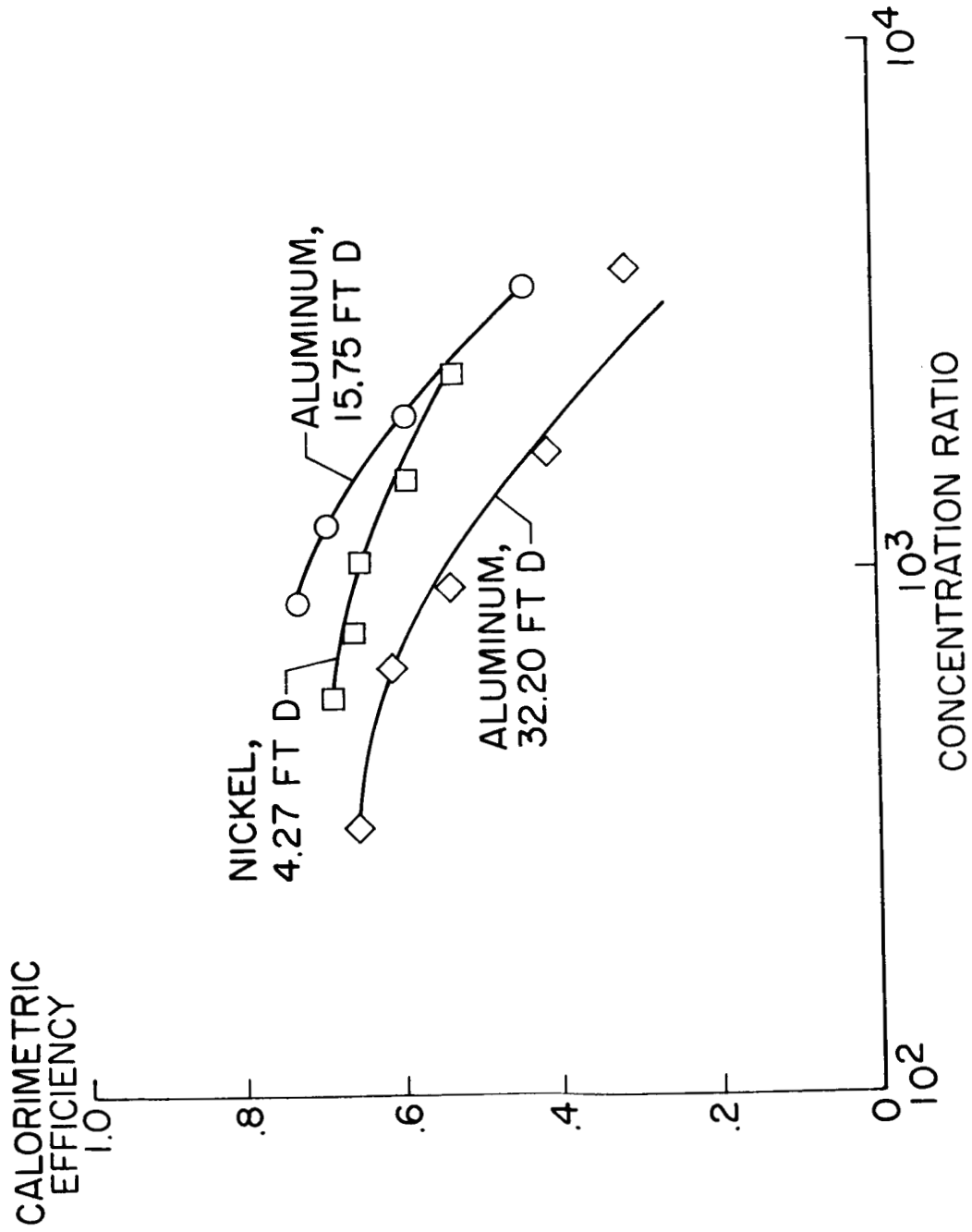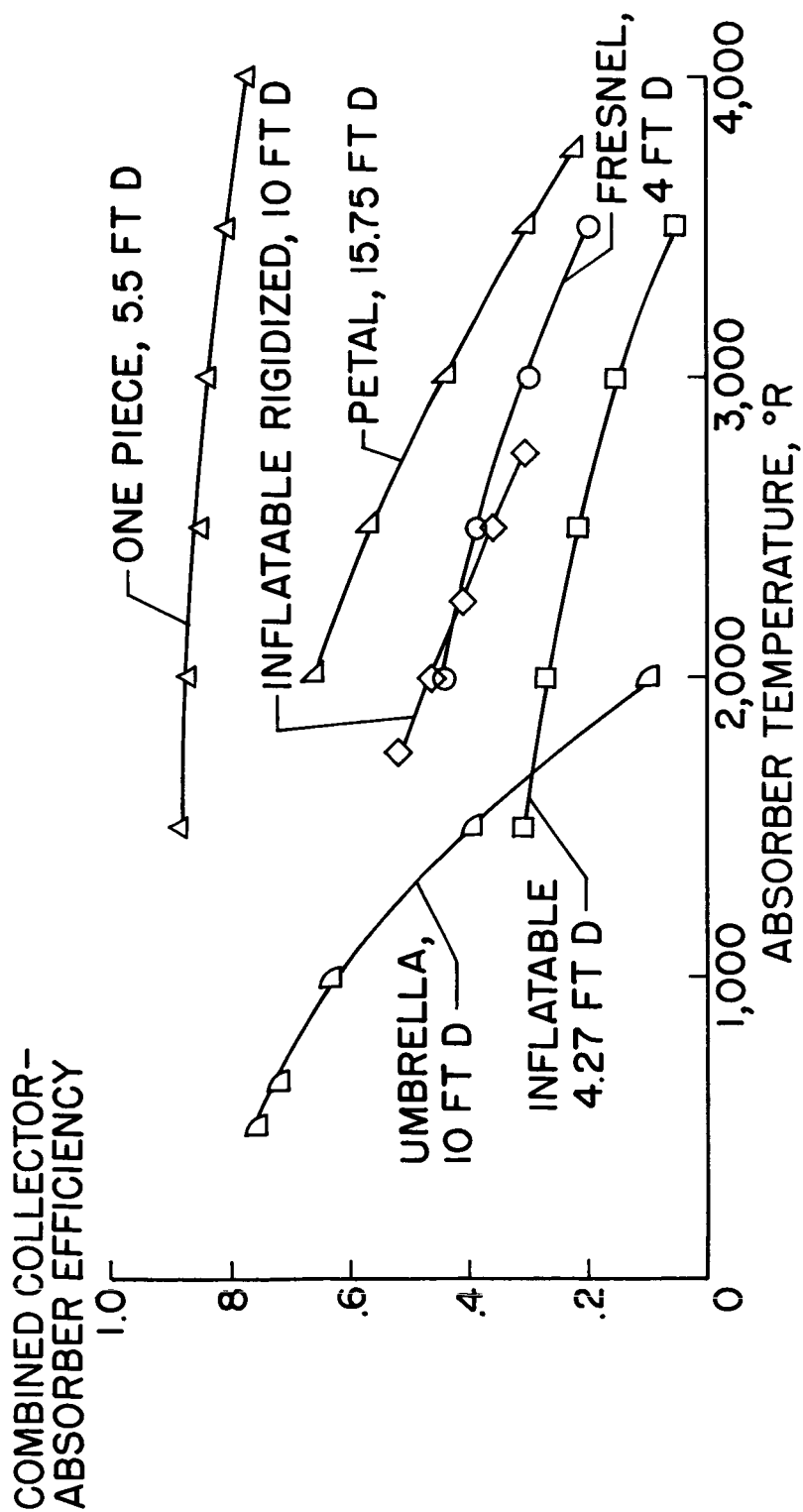PLASTIC, 5.0 FT D

CONCENTRATION RATIO

10^2 10^3 10^4

NASA

Figure 3.- One-piece collectors.

Figure 4.- Petal collectors.
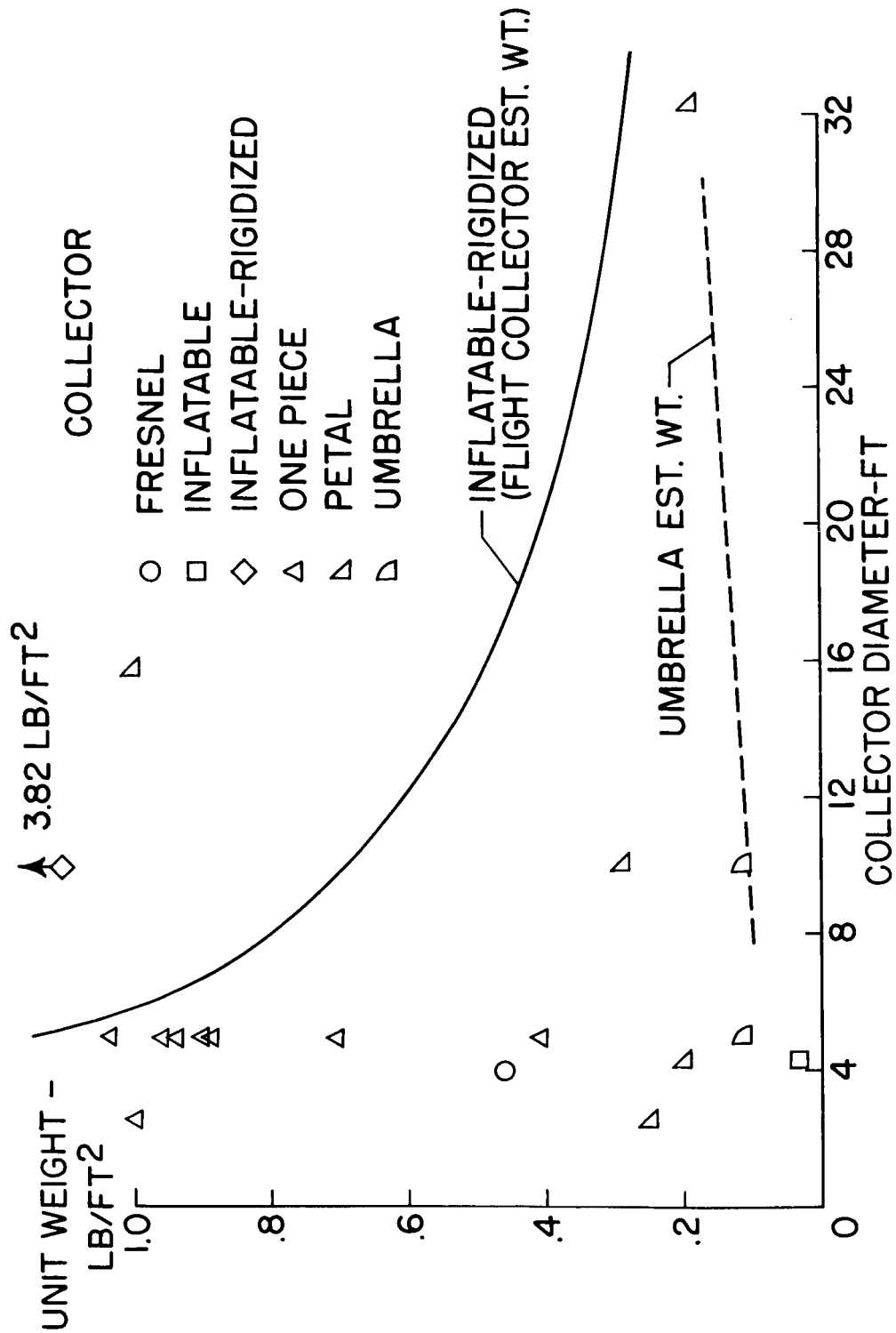
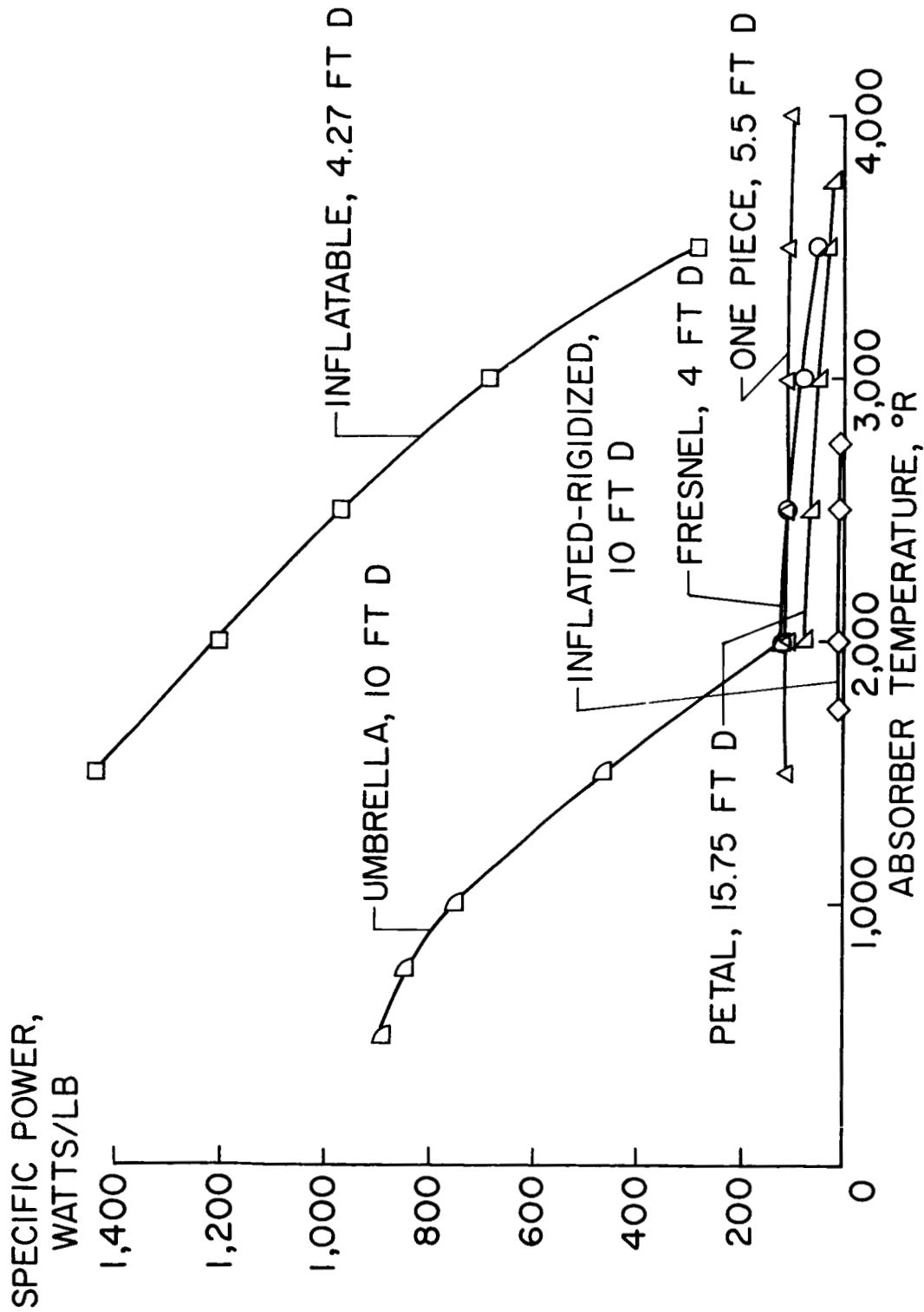NASA

Figure 5.- Combined collector-absorber efficiencies.
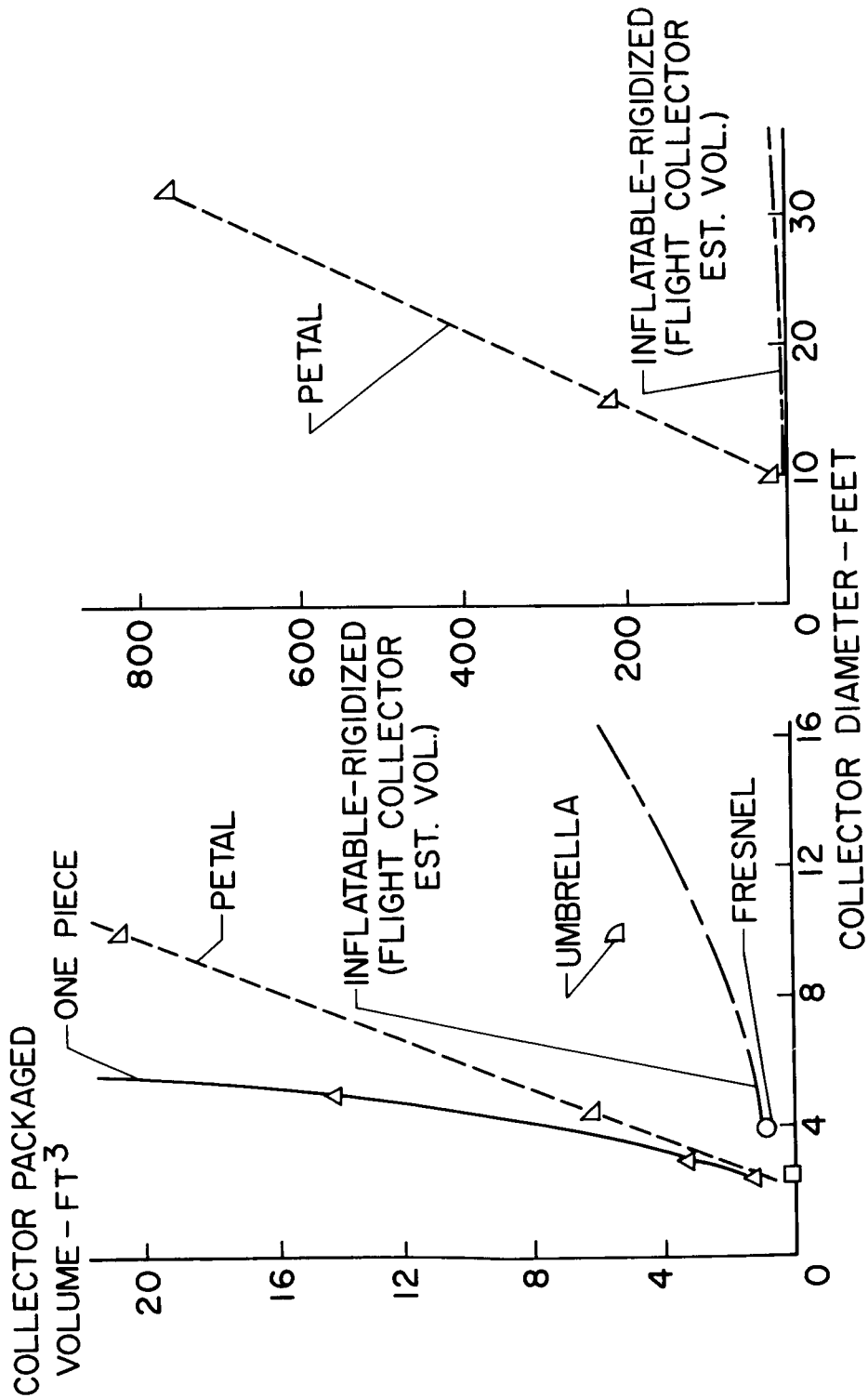
Figure 6.- Collector unit weight.

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Figure 7.- Collector specific power.

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Figure 8.- Collector packaged volume.

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